NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

CHARACTERIZATION AND MAGNETIC AUGMENTATION OF A LOW VOLTAGE ELECTROMAGNETIC RAILGUN

by

John P. Hartke

December, 1997

Thesis Advisor: Richard Harkins

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE December 1997	3. REPORT TYPE AND DATES COVERED Master'sThesis

4. CHARACTERIZATION AND MAGNETIC AUGMENTATION OF A LOW VOLTAGE ELECTROMAGNETIC RAILGUN	5. FUNDING NUMBERS
6. AUTHOR(S) Hartke, John P.	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

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To investigate electromagnetic launch technologies and the effects of augmentation a 44 cm railgun was constructed and tested. The railgun was powered by a capacitor bank of fourteen 330 V, 600 μF capacitors. The velocity of the projectile, the voltage across the capacitors and the current through the rails were measured. The augmentation of the gun with a permanent magnetic field increased the velocity of the projectile by 85% while air injection augmentation had no effect.

14. SUBJECT TERMS *Electromagnetic Railgun, Electromagnetic Launch Technology, Railgun Augmentation.	15. NUMBER OF PAGES 53
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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CHARACTERIZATION AND MAGNETIC AUGMENTATION OF A LOW VOLTAGE ELECTROMAGNETIC RAILGUN

John P. Hartke
Captain, United States Army
B.S., United States Military Academy, 1988

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1997

ABSTRACT

In the near future armored vehicles will be fielded with reactive armor which can not be defeated by today's chemically propelled munitions. Today's munitions are limited to muzzle velocities less than the speed of sound in the chemical propellant which is about 1.8 km/s. Electromagnetic launch technologies have the ability to launch projectiles at velocities in excess of 2 km/s and may be able to defeat the reactive armor. Not only can electromagnetic launch technologies be used as an anti-tank weapon but it can also be used as anti-missile defense.

To investigate electromagnetic launch technologies and the effects of augmentation a 44 cm railgun was constructed and tested. The railgun was powered by a capacitor bank of fourteen 330 V, 600 μF capacitors. The velocity of the projectile, the voltage across the capacitors and the current through the rails were measured. The augmentation of the gun with a permanent magnetic field increased the velocity of the projectile by 85% while air injection augmentation had no effect.

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ACKNOWLEDGEMENT

I am grateful for the support from The Naval Postgraduate School on this work. I would also like to thank R. M. Harkins, W. B. Maier, and X. K. Maruyama for their technical assistance and guidance. The expert machining services and insightful suggestions of Gary Beck and George Jaksha were instrumental in the construction and maintenance of the gun. My deepest appreciation goes to Don Snyder and Harold Rietdyk who truly made everything happen from design to construction to testing they were there every step of the way with timely advise, tremendous hard work, and patience. Finally I owe a special debt of gratitude to my wife Lisa and children, Matthew and Alexandra, for the time that should have been theirs.

I. INTRODUCTION

A. SCOPE

The scope of this work is to examine some of the potential military applications of electromagnetic (EM) launch technologies, to characterize the electrical output of a capacitor powered EM launch system, and quantify the contribution of different augmentation techniques with a low voltage 44 cm electromagnetic launcher.

B. HISTORY

Since the start of warfare man has been looking for ways to propel objects at his adversaries with ever increasing efficiency. Man was first locked into hand to hand combat until the catapult and eventually the bow and arrow dramatically shifted the way battles were fought. These technologies were limited by the amount of energy which could be stored in the mechanics of the catapult or muscle of the archer. In the early 1300's chemical explosives provided the next leap forward and allowed objects to projected out of high pressure guns. Today's conventional rifles, artillery, and armored vehicles fire projectiles with velocities which are limited by the speed of sound of the expanding chemical explosives. Rocket assisted projectiles are limited by the amount of rocket fuel they can carry on board, and the useful payload of most rockets is only about one percent of the launch mass. In addition to the velocity limitations of the chemical explosives, there is the risk of a premature explosion.

Electromagnetic launchers overcome the velocity limitations of chemically propelled projectiles and decrease the risk of premature detonation. Electromagnetic launching is "the acceleration of an object by electromagnetic forces along a guide way to initiate subsequent free flight."[1] The study of electromagnetic launchers has been going on for over 90 years with over 45 patents issued before World War II. One of the first EM guns was the "Patent Electric Cannon" conceived by Birkeland in 1901. Fauchon-Villeplee published the book *Cannons Electrique* in 1920 and there are examples of

German and Japanese work in the area during World War II. The US Navy and Air Force also sponsored studies on EM technologies in the 1950's. The first break through was achieved by Richard Marshall and his colleagues at The Australian National University when they accelerated a 3 gram Lexan projectile to 5.9 km/s with a plasma arc armature in a gun system that was evacuated to 0.1 Torr.[2] In 1978 the US Department of Defense began to assess the viability of EM technologies and provide a focus for the national effort. An advisory panel was formed and a workshop was held at the US Naval Academy in December 1978. [1] In 1992 the US Army initiated a comprehensive Focused Technology program and the Center for Electromagnetic - University of Texas (CEM-UT) was formed to take the lead in research and development.[3]

Currently the US has two major facilities capable of launching projectiles to 9 MJ. The guns, one located Green Farm in California operated by the Defense Nuclear Agency and the other at CEM-UT, can both accelerate 1-2 kg projectiles to 2.5 - 4 km/s. They are used to test projectile and armature designs.[4]

C. A CASE FOR ELECTROMAGNETIC RAILGUNS

Although the EM launcher fires projectiles faster than chemical propulsion weapons, this does not necessarily justify a military use. The current generation of armored vehicles are fielded with a reactive armor designed to defeat high explosive anti-tank (HEAT) rounds. This technology is also effective against kinetic energy or SABOT rounds. Reactive armor advancements could make armored vehicles impenetrable to today's chemically propelled munitions in the next decade. The maximum velocity of the conventional munitions is around 1.8 km/s. At this velocity, the SABOT penetrators will be deflected by the reactive armor. Studies conducted at the University of Texas at Austin have shown that the reactive armor is more vulnerable to hypervelocity projectiles for three basic reasons. The first is the effective yaw angle is less at hypervelocity, so the projectiles are damaged less by the reactive armor interaction. Second, because of the higher velocity, there is less time for the projectile to react to the non-axial forces as it

traverses the reactive armor. Finally, because crater diameters are larger at hypervelocity, the degradation in penetration behind the reactive armor due to yaw will be less.[5] The electromagnetic railgun, on the other hand does not have a theoretical velocity limitation and can therefore launch projectiles at the hypervelocities which will defeat the reactive armor. Air friction will limit the projectile velocity as the heat from the friction melts and erodes the projectile. Tungsten has been fired at 3 km/s with neglible erosion.

D. POSSIBLE MILITARY USES FOR ELECTROMAGNETIC RAILGUN TECHNOLOGY

1. Tanks

The railgun has possible anti-tank weapon system applications. One of the most lethal weapons on the battle field during Operation Desert Storm was the M1A1 tank firing SABOT or kinetic energy rounds. The SABOT round is a long hard penetrator which travels with enough kinetic energy to penetrate most known armor except for the new generation of reactive armor. Reactive armor blows out when triggered, absorbing most of the kinetic energy of the SABOT and preventing penetration. The railgun can shoot SABOT like rounds with enough energy and velocity to defeat reactive armor and penetrate the hull. The higher velocities also translate into longer ranges and increased accuracy. The increased accuracy comes from reduced time of flight which reduces the target's reaction time and reduces the amount of time other forces may act on the projectile while in flight.

Not only does electromagnetic launcher technology increase the lethality of the tank but also dramatically increases its survivability. The most vulnerable part of the tank other than the top is the ammunition storage racks. The probability of kill is directly related to where the penetrator hits the armored vehicle. A shot to the crew compartment will cause crew casualties but the vehicle can be used again with normally minor repairs.

A shot to the engine compartment will cause more significant damage to the tank but can probably be repaired and crew would have a greater chance of survival. A shot to the ammunition storage areas will cause a catastrophic kill to the vehicle and the crew because of the secondary explosions of the ammunition propellants. By using a railgun on the tank there will no longer be a need for explosives propellants on the tank and therefore a shot to the ammunition storage area will result only in minor damage to the vehicle and crew.

Another advantage to railguns is a savings in logistics. The tank will now be able to carry more EM launched rounds of ammunition, provided the power supply and pulse forming network do not take up significantly more space than they do now. The diameter of the rounds for the railgun need only be as big as the actual penetrator which is about 3 cm where as the diameter of today's SABOT rounds is 12 cm. This alone allows a tank which would carry 40 rounds the ability to carry 640. Additionally, the railgun round is lighter than conventional rounds because the weight of the propellant and heavy casing is eliminated.

This savings in space and the additional survivability of tank due to the lack of explosives on board is magnified in the logistics of supporting armored forces. As an example, consider the Heavy Expanded Mobility Tactical Truck (HEMTT) which brings the ammunition from the combat trains forward to the tanks on the battlefield. Using today's ammunition a HEMTT cargo truck can transport a couple hundred rounds of ammunition limited by the weight. The railgun rounds which are about 1/16 the size of today's rounds. This translates into the HEMTT cargo truck carrying thousands more EM launched rounds of the same size and weight as today's penetrators.

2. Ballistic Missile Defense System

One of the significant threats to the US military forces and US population is the proliferation of ballistic missile technologies to terrorist and third world rogue nations. With the end of the Cold War, these groups may see a ballistic missile attack on US forces

in their region or even an attack on a US city as a viable means to assert their control over the situation and to influence the US will to act. Therefore there has been significant work in the areas of theater and strategic missile defense. One of the identified holes in the development of the missile defense has been in the area of boost phase intercept. The boost phase defense becomes important as munitions are developed which would deploy nuclear, chemical or biological sub-munitions immediately after booster cut-off. The challenge for boost phase intercept is that the system must intercept and destroy the target within one hundred seconds of targeting. The only current technologies which may be able to meet the one hundred second engagement time are the airborne laser and space, air, or ground based EM guns.[6]

3. Magnetic Fusion Reactor Refueling

One of the non-military uses of electromagnetic launch technology is for the acceleration of solid hydrogen pellets for magnetic fusion reactor refueling. An accepted method for refueling a magnetically confined fusion reactor is to inject hypervelocity frozen hydrogen pellets. The 4-5 mg pellets require a velocity on the order of 10 km/s. Current techniques include centrifugal injectors and light gas guns. Railgun technology provides promise in meeting these requirements, and work is being done at the University of Illinois at Urbanan-Champain.[8,9]

E. CURRENT ISSUES AND LIMITATIONS

1. Pulse Power and Energy Storage

For effective use of electromagnetic launch technology on combat vehicles, the energy storage device and pulse forming network has to be as rugged and compact as

possible. Dr. Ian McNab from the Institute of Advanced Technology at the University of Texas at Austin, sized the energy storage requirements. He found that for the Future Main Battle Tank (FMBT) assuming a sustained four rounds a minute firing rate, the typical gun parameters are 30-40 MJ, 5-7 kV, a 4-6 ms pulse length, 3-4 MA of current, and 2000 kW of average power. There are several energy storage devices for the EM launcher which have shown promise and are summarized in Table 1.1. Two of the more promising techniques for energy storage are chemical batteries and fly wheels. Batteries can store a lot of energy per kilogram, but they have low power ratings and low DC voltages. Flywheels require significant support subsystems and hardening for combat vehicle use. In either case the storage system could be used to power not only the weapon system but, with some significant technological advances, also power the automotive and peripheral systems making the FMBT an "electric" tank.[10]

Once the energy storage system is established, the power for the EM launcher must be pulsed-formed for maximum efficiency. The most widely accepted pulse shape is to have a fast current rise time into the rails, (but not so fast that there is a significant jerk; where jerk is the time rate of change of the acceleration) a flat constant current for most of the acceleration, and a quick fall time as the projectile reaches the end of the barrel to reduce the muzzle flash.[10]

One method of achieving a flat top is called Distributed Energy Stores (DES). This design has multiple current feed points placed along the barrel, spaced and timed to fire in sequence maintaining the constant current through the discharge. This technique has showed some promise not only in forming the pulse but in the physical design of the gun barrel. This method also leaves open the technique of storing and delivering the pulses to the rails. Another method is a capacitor bank where the capacitors are connected in parallel and an inductor is placed between the adjacent capacitors to lengthen and form the current pulse (Figure 1.2.). The capacitor bank is then connected directly to the breech of the rails or to a trans-augmented rails in series with launch rails. Trans-augmentation is discussed later. Capacitors have been the system of choice for most lab

work because of their low cost, and they are the storage method used in the present investigation.

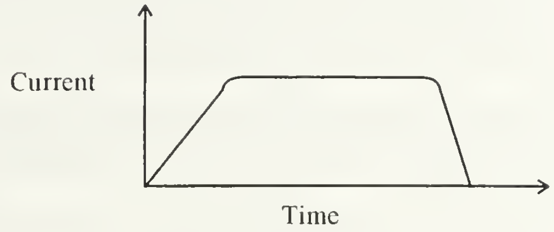

Figure 1.1 Railgun Current Pulse

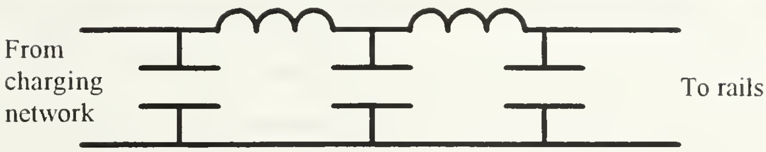

Figure 1.2 Capacitor/Inductor PFN

The US Army has been interested in the development of the air-cored pulse alternator as the energy storage technique for the EM launcher. The pulse alternator uses rotating disks and drums to store the energy and is discharged through an AC rectifier prior to delivering it to the rails. To fit this design into a tactical vehicle requires high rotational speeds with lightweight and strong rotor construction and materials.

Table 1.1 Energy Storage Mechanisms From Ref [10]

Device	Method	Equation	Assumption	Typical State-of-the-art parameters	Energy Density (MJ/m^3)
Capacitor	Electrostatic	$E = \frac{\varepsilon E^2}{2}$	High energy density plastic film	E_{op}= 400 V/m ε_r=10	7
Rotor	Inertial	$E = \frac{I_M \omega^2}{2}$	High speed composite/ conductor rotor	ρ = 1500 kg/m^3	135
Inductor	Magnetic	$E = \frac{B^2}{2\mu_r \mu_o}$	High field air cored inductor	μ_r=1 B=40T	640
Battery	Electrochemical		LiMS * operating at 480 C	1.72 V	4,000
Flux compressor	Chemical		High energy density materials	Few eV/bond	5,000-10,000

* LiMS batteries are litium metal sulphide, which use molten salts as the medium to transfer current between the electrodes.

These energy storage techniques and delivery means continue to be investigated. To achieve a design which could fit in a tank the energy storage densities must be dramatically increased. In addition to the energy densities the energy transfer mechanisms must also be improved to increase the overall efficiencies. In many cases a rectifier or transformer is needed to adapt the power supply to the high current requirements of the rails.[10]

2. Rail Life and Design

One of the hurdles yet to be overcome prior to placing an EM launcher on an armored vehicle is the development of rails which can sustain many shots and field environments. The tremendous amount of current passing through the rails and armature often creates an arc. Arcing significantly reduces the rail life by causing pitting and scarring along the rails from the high temperatures. The pitting and scarring reduces the contact between subsequent rounds and causes more arcing and wear. The arcing is also the most significant energy loss mechanism for the EM system. The other challenge to practical railgun design is making a barrel which is stiff enough to handle the varying weather conditions which armored vehicles have to fight in and light enough for the hydraulics of the tank to manipulate. Even today's 120mm gun tubes experience gun droop. As the temperature warms during the day, the gun tube has a tendency to deflect downward. Current tanks have quick methods for the crew to adjust for droop. For railguns the problem is amplified by the fact that as the barrel droops, rail alignment can change. Because of the tight tolerances required for the armature-rail fit, any change in the gap between the rails can cause significant arcing or make the barrel too small for the round.

3. High Explosive Rounds

Current work in railgun technology is focused on firing kinetic penetrator rounds whereas today's tanks fire both SABOT and High Explosive Anti-Tank (HEAT) rounds. The HEAT round contains composition B and C explosives which if not protected from the high currents passing through the armature could cause detonation in the barrel. Also the fuse mechanism may need to be redesigned so that the drag forces from the high velocity do not cause premature detonation. HEAT rounds are used on soft targets like lightly armored personnel carriers, trucks, bunkers and buildings.

II. THEORY

A. FORCE

1. Lorentz Force

The force which acts on the projectile in an electromagnetic railgun is the Lorentz force ($\vec{F} = q\vec{v}_d \times \vec{B}$). The railgun is constructed with two current carrying parallel rails with a conducting armature connecting them. The current traveling through the rails creates a magnetic field between the rails by the right hand rule. The current through the armature is characterized by the drift velocity of the electrons between the rails.

Consider the force acting on a differential element of current carrying wire immersed in a uniform magnetic field. The electrons will flow through a plane in the wire in a time dx/v_d (where v_d is the drift velocity of the electrons). The charge carried by the wire through the plane is then given by:

$$q = I\left(\frac{dx}{v_d}\right). \qquad (2.1)$$

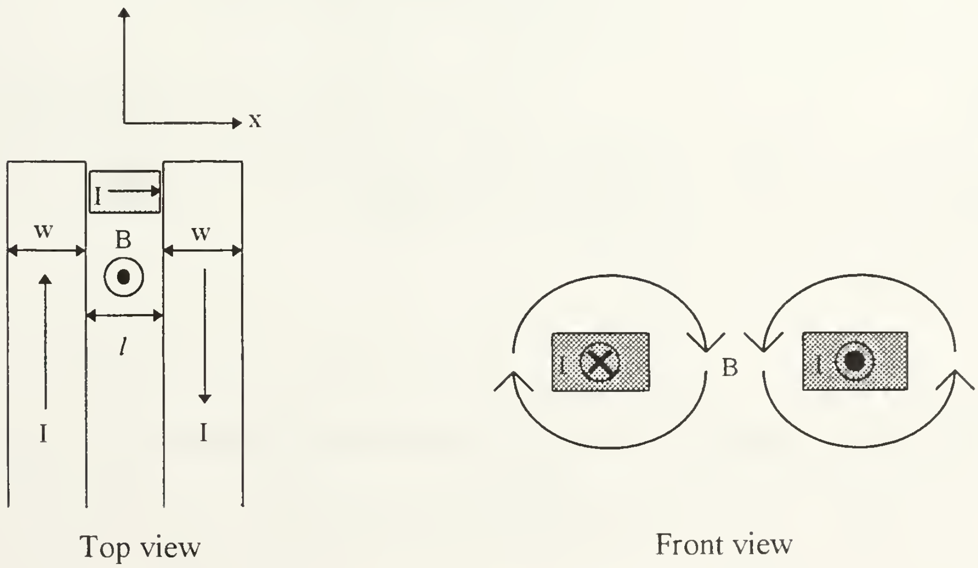

Figure 2.1. Magnetic field created by parallel conducting bars

Substituting equation 2.1 into equation for the Lorentz force:

$$d\vec{F} = d\, q\vec{v}_d \times \vec{B}, \tag{2.2}$$

yields:

$$d\vec{F} = I\, d\vec{x} \times \vec{B} \tag{2.3}$$

or

$$dF = BI\, dx. \tag{2.4}$$

Where the force is acting in the direction given by the right hand rule of the current crossed with the magnetic field.

To determine the magnetic field created by the current through the rails consider the magnetic field created by a long straight wire. From the Biot-Savart law:

$$B = \frac{\mu_o I}{2\pi\, r}. \tag{2.5}$$

Assuming that all of the current passes through the center of the rails of width "w", separated by a distance "l", and with the origin half way between the rails; the strength of the magnetic field at a point x between the rails is:

$$B = \frac{\mu_o I}{2\pi}\left[\left(\frac{1}{\frac{l+w}{2}+x}\right)+\left(\frac{1}{\frac{l+w}{2}-x}\right)\right]; \tag{2.6}$$

where: $$\frac{-(l+w)}{2} \le x \le \frac{(l+w)}{2}.$$

Figure 2.2 is a plot of the magnetic field strength between the rails created by a 3 kA current through 1.5 cm wide rails with a 7 cm gap.

Letting

$$y = \frac{l+w}{2} \Rightarrow \frac{l}{2} = y - \frac{w}{2}, \tag{2.7}$$

and substituting into equation 2.6 one finds the equation for the force to be:

$$F = \frac{\mu_o I^2}{2\pi}\int_{\frac{w}{2}-y}^{y-\frac{w}{2}}\left(\frac{1}{y+x}+\frac{1}{y-x}\right)dx. \tag{2.8}$$

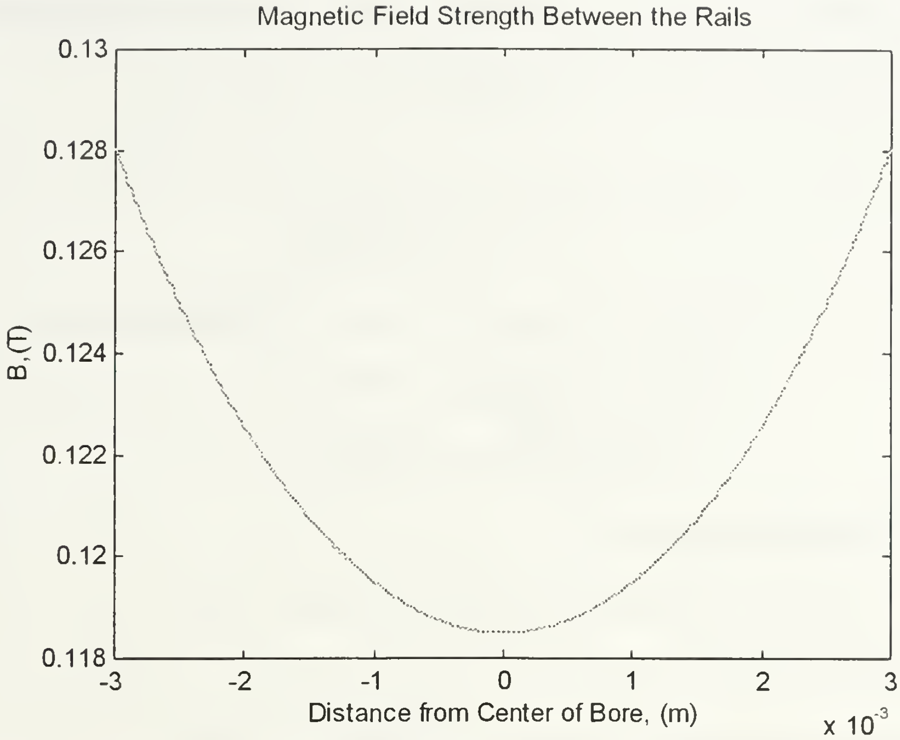

Figure 2.2 Magnetic Field Strength Between the Rails

Solving this integral yields:

$$F = \frac{\mu_0 I^2}{2\pi} \ln\left(\frac{(4y-w)^2}{w^2}\right). \tag{2.9}$$

Substituting the original parameters back:

$$F = \frac{\mu_0 I^2}{2\pi} \ln\left(\frac{(2l+w)^2}{w^2}\right). \tag{2.10}$$

2. As a Circuit

We can also derive an expression for the force exerted by a railgun system if we consider the electric circuit. We can model the system as a capacitor, C, charged to a voltage, V, in series with an inductor, L_o, and a resister, R. The railgun is modeled as an

inductor, L_r, which varies as a function of the displacement of the armature and a projectile with mass, m; energy, E; and velocity v.

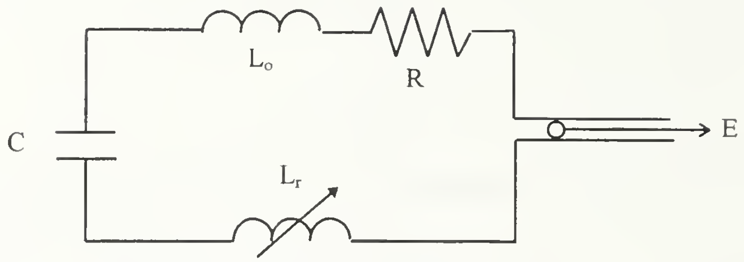

Figure 2.3 Ideal Railgun Circuit

By conservation of energy:

$$\frac{1}{2}mv^2+\frac{1}{2}CV^2+\frac{1}{2}LI^2+\int I^2R\,dt=\frac{1}{2}CV_o^2 \qquad (2.11)$$

where $L=L_o+L_r$.

Taking the derivative of both sides with respect to x yields:

$$mv\frac{dv}{dx}+CV\frac{dV}{dx}+\frac{1}{2}\frac{d}{dx}\left(LI^2\right)+\frac{1}{v}I^2R=0. \qquad (2.12)$$

Substituting

$$mv\frac{dv}{dx}=m\frac{dv}{dt} \quad \text{and} \quad -C\frac{dV}{dx}=\frac{I}{v},$$

yields

$$m\frac{dv}{dt}=\frac{IV}{v}-LI\frac{dI}{dx}-\frac{1}{2}I^2\frac{dL}{dx}-\frac{I^2R}{v}. \qquad (2.13)$$

Letting

$$E=1/2\ mv^2 \quad \text{and} \quad \frac{dL_o}{dx}=0;$$

$$\frac{d}{dt}E=VI-\frac{1}{2}vI^2\frac{dL_r}{dx}-LIv\frac{dI}{dx}-I^2R. \qquad (2.14)$$

Now apply Kirchhoff's Law to the circuit

$$V-L_o\frac{dI}{dt}-RI-\frac{d}{dt}\left(L_rI\right)=0. \qquad (2.15)$$

Multiplying through by I and putting all derivatives with respect to x yields:

$$\mathrm{VI} - \mathrm{LI}\,v\frac{d\mathrm{I}}{dx} - \mathrm{RI}^2 - v\,\mathrm{I}^2\,\frac{d\mathrm{L}_r}{dx} = 0. \tag{2.16}$$

Subtracting equation 2.16 from equation 2.14 yields an equation for force

$$\mathrm{m}\frac{dv}{dt} = \frac{1}{2}\mathrm{I}^2\frac{d\mathrm{L}}{dx}\,. \tag{2.17}$$

To compare this result with equation 2.10 we must characterize $d\mathrm{L}/dx$. It has been shown that the inductance of parallel rectangular conductors is [11]:

$$\mathrm{L} = \frac{\mu_o \mathrm{x}}{\pi}\left(\ln\frac{l+\mathrm{w}}{\mathrm{w}+\mathrm{h}} + \frac{3}{2} + \Delta_k - \Delta_e\right), \tag{2.18}$$

where l, h, w and x are defined as in figure 2.4 and Δ_e and Δ_k are defined in table 2.1. Equation 2.18 and Tables 2.1 and 2.2 assume uniform current distribution over conductor cross section, but at higher frequencies like those experienced here the inductance is somewhat less due to skin effects.

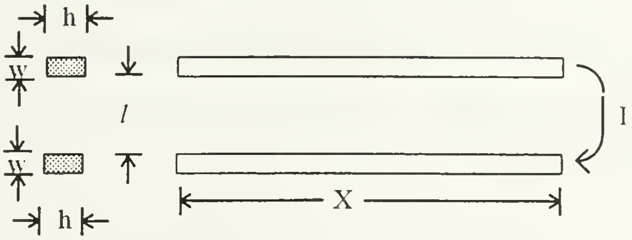

Figure 2.4 Rail Geometry

Table 2.1 Values for Δ_k from Ref [11]

h/(l+w)	0	0.5	1.0	2.0	10
w/h = 0	0	0.0199	0.0708	0.2107	1.0787
w/h = 0.5	0	0.0152	0.0560	0.1754	-
w/h = 0.75	0	0.0092	0.0359	-	-
w/h = 1.0	0	0.0005	0.0065	-	-

Table 2.2 Values for Δ_e from Ref [11]

w/h	0	0.25	0.50	0.75	1.00
Δ_e	0	0.00249	0.00211	0.00184	0.00177

Taking the derivative of equation 2.18 with respect to x, ignoring the contributions of Δ_e and Δ_k and substituting into equation 2.17 yields an equation for the force:

$$F = \frac{\mu_o I^2}{2\pi}\left(\ln\frac{l+w}{w+h} + \frac{3}{2}\right). \tag{2.19}$$

Comparing this result with equation 2.10 we find they are similar in form and magnitude.

Now that we have an equation for the force, we can solve for the velocity of the for comparisons to experiment. Solving for the acceleration of the projectile of mass m:

$$a = \frac{\mu_o I^2}{2 m \pi}\ln\left(\frac{2l+w}{w}\right)^2 \quad (2.20a) \qquad \text{or} \qquad a = \frac{\mu_o I^2}{2 m \pi}\left(\ln\frac{l+w}{w+h} + \frac{3}{2}\right). \quad (2.20b)$$

We can predict the velocity of the projectile by integrating the acceleration with respect to time. The current in equations 2.20 is the instantaneous current passing through the armature. Therefore:

$$v = u + \frac{\mu_o}{2 m \pi}\ln\left(\frac{2l+w}{w}\right)^2 \int_0^t I^2\, dt \tag{2.21a}$$

or

$$v = u + \frac{\mu_o}{2 m \pi}\left(\ln\frac{l+w}{w+h} + \frac{3}{2}\right)\int_0^t I^2\, dt. \tag{2.21b}$$

Where u is the initial velocity of the projectile prior to the initiation of the current pulse. By knowing the shape of the current pulse we can now predict the muzzle velocity of railgun.

B. AUGMENTATION TECHNIQUES

1. Permanent Magnets

There are techniques which can augment the railgun and increase the force on the projectile. One of the more straightforward techniques is to augment the rails with permanent magnets. By placing the magnets above and below the rails creating the magnetic field in the same direction as the field created by the current will increase the force on the projectile. The Lorentz force on the projectile from the permanent magnetic field B_m is:

$$F = I l B_m \,. \tag{2.22}$$

Adding this to the force due to the current through the rails yields:

$$F = \frac{\mu_o I^2}{2\pi} \ln\left(\frac{2l + w}{w}\right)^2 + I l B_m \tag{2.23a}$$

or

$$F = \frac{\mu_o I^2}{2\pi}\left(\ln\frac{l + w}{w + h} + \frac{3}{2}\right) + I l B_m \,, \tag{2.23b}$$

depending on whether equation 2.20a or 2.20b is used for acceleration.

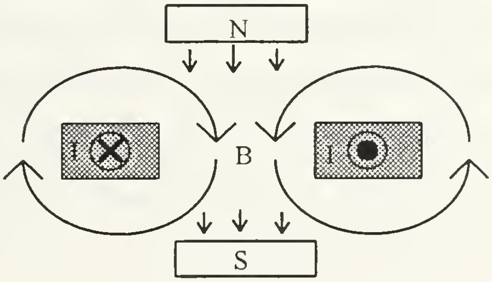

Figure 2.5 Permanent Magnet Augmentation

2. Kick Start

Another important augmentation to the rail gun is a kick start. If the projectile has an initial velocity when the current is applied the electromagnetic forces do not have to overcome the static friction. There are several methods of providing the initial velocity. The techniques range from conventional explosives to gas injectors to mechanical spring injectors. Gas injectors seem to be the method of choice because of the extremely high pressures the gasses can exert without causing damage to the conducting surfaces as a conventional explosive might. Also, the gas used can be one which ionizes easily and becomes a plasma which may assist in the carrying of current directly behind the projectile and contribute to the force on the projectile.

3. Trans-augmented Railgun

A third augmentation technique which was not used in this work is trans-augmentation. Instead of just using two rails it is possible to increase the velocity of the projectile by having two sets of rails. The magnetic field effecting the projectile can be increased by placing another set of high current carrying wires parallel to the rails. The augmentation rails can be placed in parallel to the original rails or in series with them.[9]

For parallel trans-augmentation a second power supply provides a current, I_a, to the outer set of rails inducing a magnetic field in the same direction as the original rails. For this method to be successful, the outer current pulse has to be longer than the inner pulse. Using the same procedure for the development of the force in equation 2.10, the force for the parallel trans-augmentation is:

$$F = \frac{\mu_o I_r^2}{2\pi} \ln\left(\frac{2l_r + w_r}{w_r}\right)^2 + \frac{\mu_o I_r I_a}{2\pi} \ln\left(\frac{2l_a + w_a}{w_a}\right)^2 . \tag{2.24}$$

The subscripts ‘r’ refer to the original rails and the subscript ‘a’ refers to the augmentation rails.

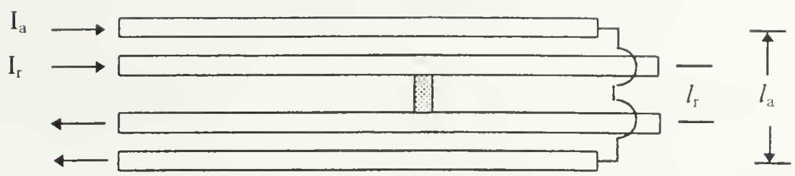

Figure 2.6 Parallel Trans-augmented Railgun

The series trans-augmentation method consists of sending a single pulse through the augmentation rails in series with the firing rails. Again a magnetic field is created by the augmentation rails. For this method to be most effective the pulse has to be long enough so that the field due to the augmentation rails is not collapsing before the projectile gets there or else the collapsing augmentation field will detract from the primary field.

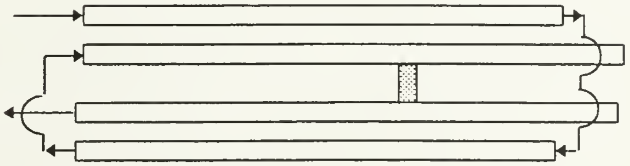

Figure 2.7 Series Trans-augmentation Railgun

The equation of force for this augmentation technique is the same as equation 2.17 but now the inductance gradient changes to accommodate the turn created by the augmentation rails.[12]

III. THE GUN

A. CIRCUIT DESIGN

The basic circuit design is a simple LRC circuit where the gun provides the inductance. A Hewlett Packard 710B power supply charges a bank of fourteen capacitors rated at 330 volts and 600 μF connected in parallel. The positive side of the capacitors connect to a $7.5 \times 10^{-4}\,\Omega$ resistor and then to a SCR switch. The resistor is used to measure the current going to the rails. Protection diodes are installed to protect the SCR switch and prevent reverse charging of the capacitor bank. The SCR is a Philips ECG5378 and is capable of conducting 8 kA.

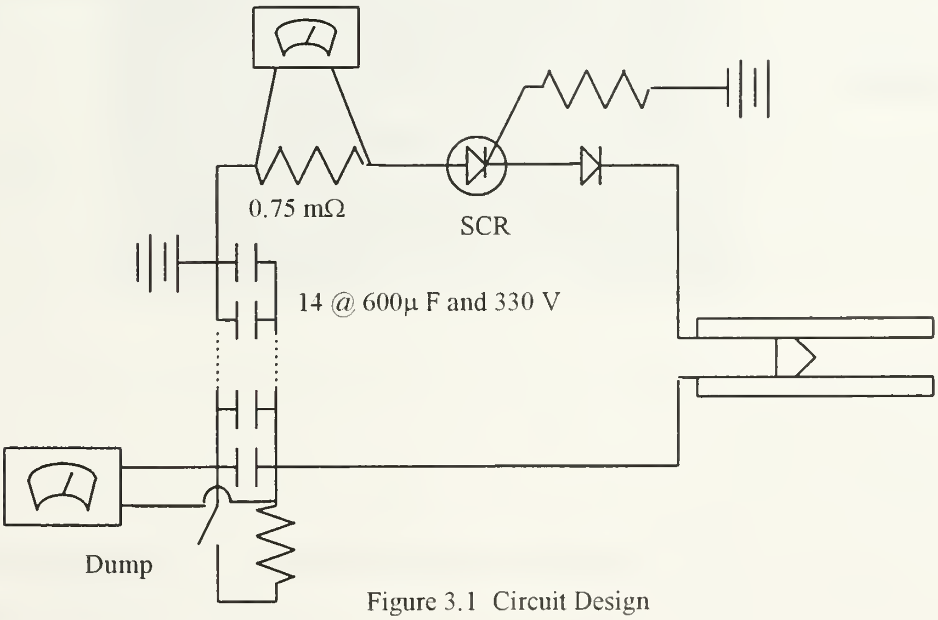

Figure 3.1 Circuit Design

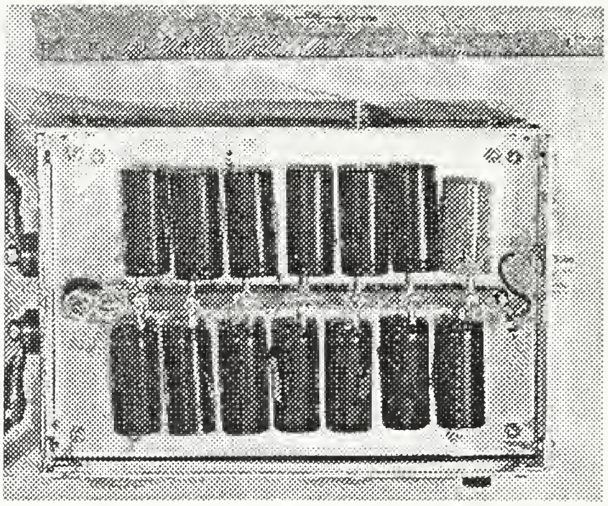

Figure 3.2 Capacitor Bank

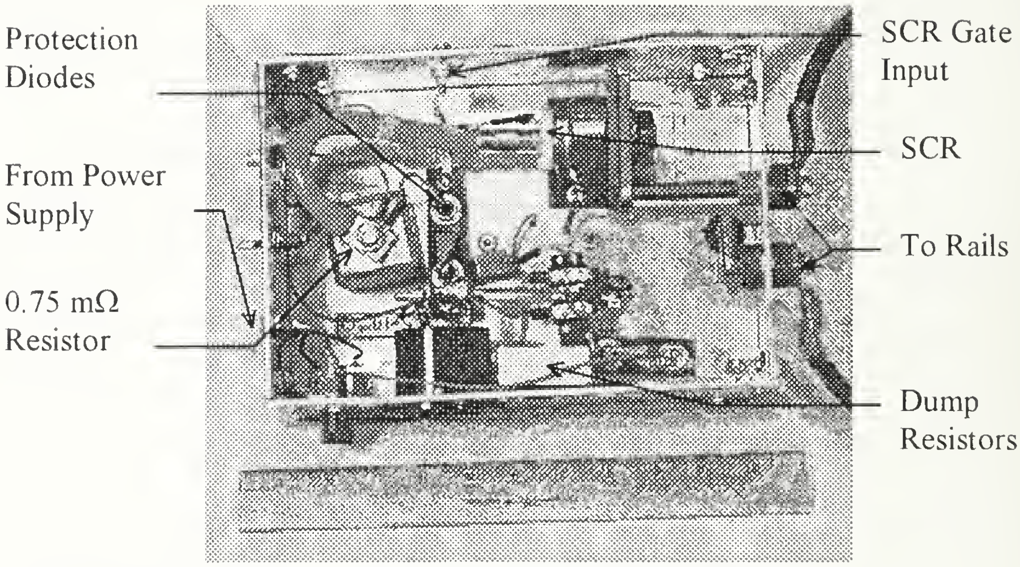

Figure 3.3 Switching and Charging Circuitry

B. RAIL DESIGN

The original rail design consisted of two pieces of bar stock copper 0.635 cm high, 1.59 cm wide, 44 cm long and separated by 0.635 cm. They were secured to 6.5 x 7.5 x 44 cm piece of phenolic which was split in half and grooved to accommodate the rails and the bore. Threaded copper studs were inserted through the top of the phenolic at the breech of the gun and screwed into the rails. The breech of the gun was sealed with

another piece of phenolic. Copper was used for the rail design because of its low cost, availability, and high conductivity.

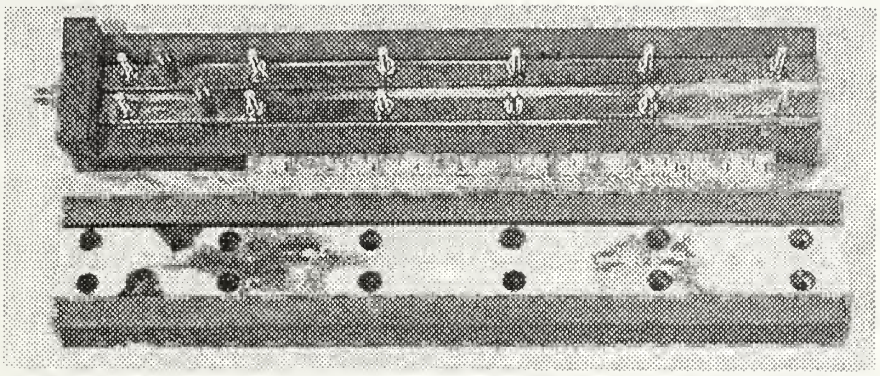

Figure 3.4 Rails

C. AUGMENTATION TECHNIQUES

An initial velocity was imparted to the projectile by the use of an air injection system. The purpose of the air injection is to overcome the static frictional forces before applying the electromagnetic forces to the armature. A low pressure air fitting was attached to the breech plate of the gun. An electronically controlled air valve was placed between the air supply and the railgun. The switch allowed a controlled 150 psi pulse of nitrogen to be injected into the breech of the gun for one second. The muzzle velocity of the projectile with only the air injection is about 8 m/s but varied significantly with the armature type.

The system was also augmented with neodymium magnets. A total of twelve magnets were fixed above and below the bore of the gun. The magnets are separated by 0.159 cm of phenolic and 0.159 cm of Teflon. The magnetic field is 0.2 Tesla in the center of the bore (point B in Figure 3.5) and 0.4 Tesla at the surface of the magnets (points A in Figure 3.5).

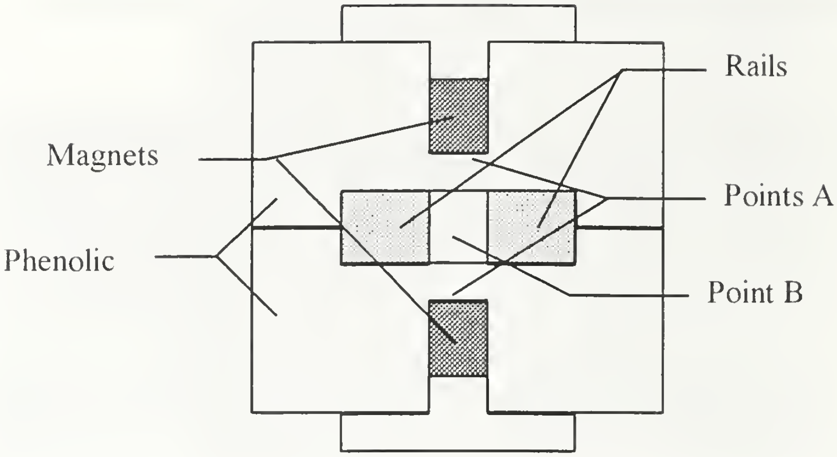

Figure 3.5 Front View of Magnetic Augmentation

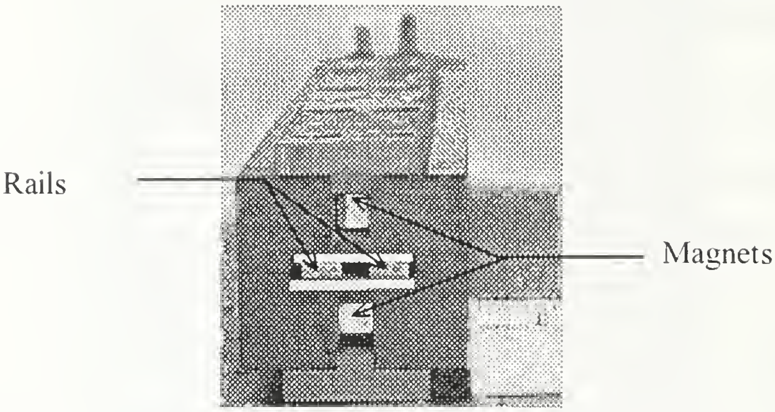

Figure 3.6 Front of Rails with Permanent Magnetic Augmentation

D. PROJECTILE DESIGN

Projectile design continues to be one of the critical areas of current research. But the measure of effectiveness of armature design is more than the projectile velocity. One of the more important measures of design effectiveness is the amount of wear the projectile causes to the rails. As discussed in the introduction rail wear is critical to the applicability of EM technology to armored vehicles. Therefore a projectile design must minimize rail effects while maximizing velocity. A third concern is preservation of the original projectile mass. If a significant amount of projectile mass is lost to the rails or

burned up in the firing process, the lower kinetic energy of the penetrator could reduce its effectiveness on target.

The first armatures used in this experiment were the solid type. A solid armature is a single piece of conductor, normally copper or aluminum, which acts as both the conductor between the rails and the penetrator. The challenge with this design is maintaining contact between the armature and the rails. Any error in the machining may create a gap between the rails and the armature, an arc will form at the gap causing pitting and erosion of the rails. The arcing also increases the resistivity of the rails and reduces the efficiency. Another problem we observed with the solid armature was that in addition to the pitting of the rails the arcing and heat generated by the high currents caused the armature to vaporize, so that a plasma was created. The plasma and molten metal would them begin to blow-by the armature and actually jam the armature in the rails.

To help combat these problems special armature geometries were used. The first modification was to make the tail of the armature a "U-shaped" or "bobbed tail". With this design the current flow and magnetic forces acting on the armature forces the arms of the projectile outwards toward the rails to help maintain contact. The second modification is to machine compression rings around the diameter of the armature. This is to absorb the blow by and prevent the projectile from jamming. The material which starts to blow-by accumulates in the grooves instead of between the rails and the armature. This design is similar to the designs of bullets used during the Civil War when the lead rounds would melt from the heat of the gun powder explosion.

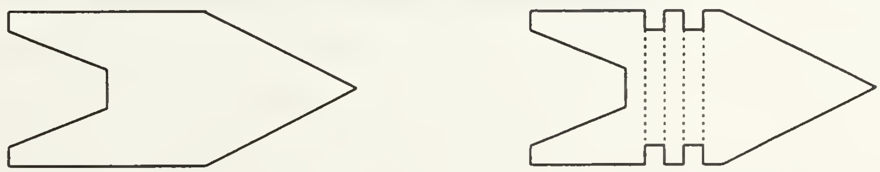

Figure 3.7 Solid armature geometry with and without grooving

The second type of armature tried was a plasma armature. A plasma armature is a thin foil or small gauge copper or aluminum wire between the breech and the back of the projectile. When the high current flows through the foil it vaporizes and creates a conducting plasma. The rest of the current continues flowing through the plasma gas which pushes the projectile out the barrel. This technique was the first to exceed the 2 km/s threshold. Rashleigh and Marshall used a plasma armature to achieve 5.9 km/s for a 3 gram lexan projectile in 1977.[2] Their work and the work of others has shown a theoretic limit of 6 km/s for a plasma armature. The limit appears to be from the "gradual expansion and lagging of the plasma armature owing to the rearward current redistribution caused by increase of the inductive counter-emf and overloading of the plasma armature with ablated matter".[13]

In an attempt to take advantage of the two designs a hybrid armature was used. The hybrid armature design consisted of a solid graphite projectile with copper "wings". The wings in this case were made of copper solder wicks attached to the graphite with super glue. The concept is that the initial current discharge turns the copper into a plasma and starts the projectile moving. As the copper melts the graphite maintains the electrical connection between the rails and acts as the solid armature.

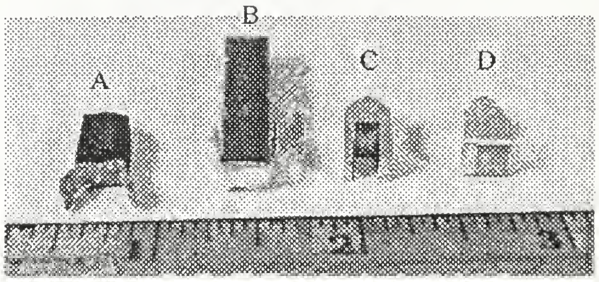

Figure 3.8 Armature Designs

A. Hybrid armature, B. Plasma armature, C. Solid armature with bobbed tail, D. Solid armature

E. MEASUREMENTS

To analyze the performance of the railgun fully it is important to understand the power supply and circuit characteristics. The current through the rails, the voltage drop across the capacitors and the speed of the projectile are three measurements of interest.

Voltage across the capacitors was measured with a digital oscilloscope between the positive and the negative capacitor terminals. The voltage drop across the capacitors was measured as a check against the current measurements and to use for the current/voltage plots.

To measure the current through the rails as a function of time, a small resistor was inserted between the capacitors and the switch. A digital oscilloscope measured the voltage drop across the resistor and a MATLAB program converted the voltage plot to a current plot. The current plots were then used to analyse the performance of the system.

To measure the velocity of the projectile a laser photodiode system was constructed. The beam from a 5 mW, 620-680 nm laser was split with one portion of the beam continuing down through a fiber optic cable to a photodiode and series of opamps. The other part of the beam traveled laterally through a focusing lens and reflected downward to another fiber optic cable and photodiode detection system. Both electrical signals were then sent to a digital oscilloscope to measure the time between breaks in the laser beams (Figures 3.9 and 3.10). The EMP generated by the railgun system interfered with the photodiode detection circuit so fiber optic cables were needed to provide the necessary stand-off. The laser beam was placed vertically as opposed to horizontally to avoid the complication of determining the vertical deflection of the projectile flight from gravity. The beams were 1/4 meter apart and the first beam was 1/8 meter from the muzzle of the gun.

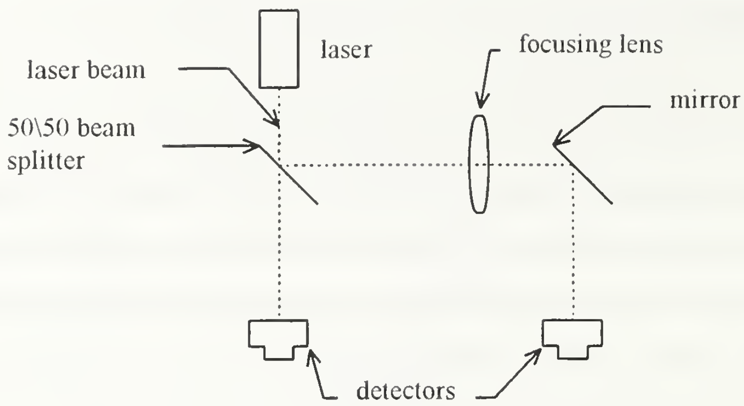

Figure 3.9 Velocity Measuring Apparatus

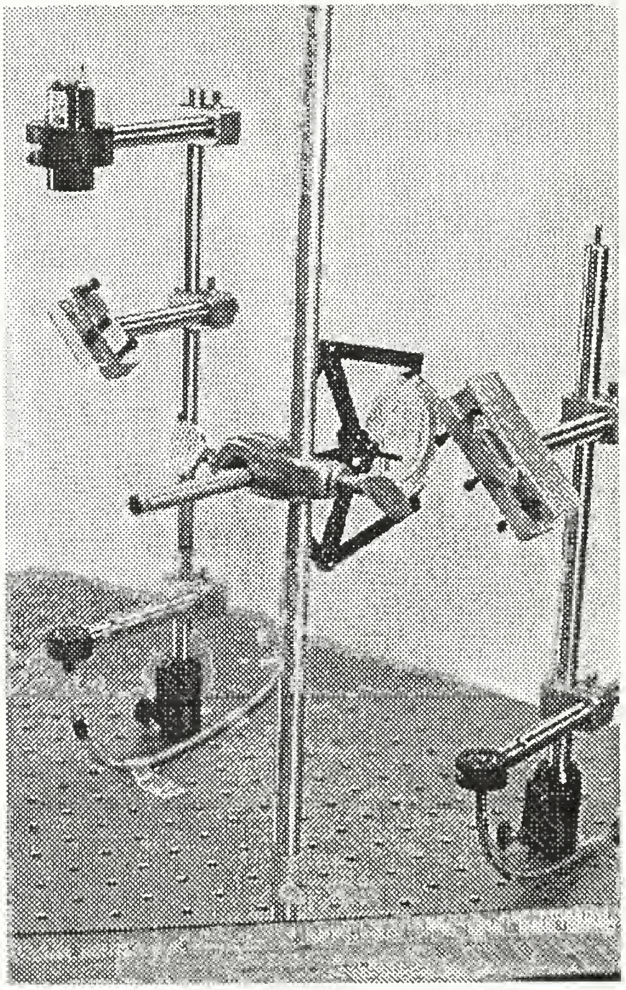

Figure 3.10 Velocity Measuring Set-up

IV. OBSERVATIONS

A. PROJECTILE DESIGN

The first successful firing of the 44 cm unaugmented gun was with a plasma armature. The projectile was a 6 x 6 x 24 mm piece of nylon with a hollowed center core. The plasma was formed by ordinary aluminum foil. The breech of the rail was sealed and a nylon spacer was placed at the breech so that the armature/projectile package was 6 cm forward of the terminals entering the rails to reduce the influence of end effects. The nylon spacer was not fixed to the rail assembly. After firing the rails showed significant pitting at the initial contact point and there was aluminum foil "welded" to the rails. The nylon spacer moved forward approximately 10 cm along the bore and the capacitors remained charged to nearly 100 volts from an initial charge of 300 volts. This firing showed that the foil disintegrated and broke the electrical connection before the entire charge could dissipate. It also showed that there was not enough plasma produced to continue the conduction. The fact that the projectile at least exited the gun is attributed to the initial expansion of the plasma and the sealed bore.

The hybrid armature design proved to be the most successful design tested. The hybrid armatures consistently fired and reached velocities of 20 m/s. The copper wick wings disintegrated in all cases and accounted for all measurable changes in mass. All but 30 volts of the 250 volt charge dissipated from the capacitor bank.

B. RAIL EFFECTS

The effects the different armatures had on the rails can be characterized by the amount of wear and residue on the rails. For the plasma armature there was significant pitting and residue. The aluminum residue was so significant that after two shots the rails had to be remachined and turned down. In an attempt to reduce the effects on the rails, carbide inserts were machined into the portion of the rails which experienced the most

pitting. The carbide was used because of its extreme hardness. The effect of the insert was reduced pitting in the carbide area but a more significant pitting at the carbide-copper interface. The carbide-copper combination was difficult to machine especially because the pitting was deeper in the copper than the carbide at the carbide-copper interface. Another attempted solution was to make tantalum inserts instead of carbide. Tantalum was used because of its extremely high melting temperatures. The thought was that the tantalum would resist the melting of the arcing aluminum. This also failed as the aluminum still welded itself to the tantalum.

The hybrid armature produced less wear on the rails than the other two armature designs and did not require machining after every five shots. In some instances successive shots were taken without any maintenance required on the rails. To try and maintain a consistent surface for all experiments, after each shot the rails were removed and lightly sanded to remove any residue that might have increased the resistance to the current flow through the armature. There was still scarring of the rails, but it was spread over a longer distance and to a shallower depth than with the plasma armature.

Based on the consistency of performance and limited effects on the rail life, the hybrid armature design was adopted and used in all later projectile experiments.

C. CHARACTERIZATION OF THE ELECTRICAL SYSTEM

To characterize the behavior of the electrical system we fired the charge into a purely resistive load of 25 mΩ. Using the fixed resister provided an accurate model for what we expected to see when actually firing, because the resistance of the armature in the rails does not change significantly as the armature traveled down the rails. Current and voltage histories for the actual rails and the restive load had similar shapes and only varied in amplitude and period.

When plotting the current and voltage as a function of time we see that the voltage drops exponentially and the current has a rise and fall time as expected for an LRC circuit.

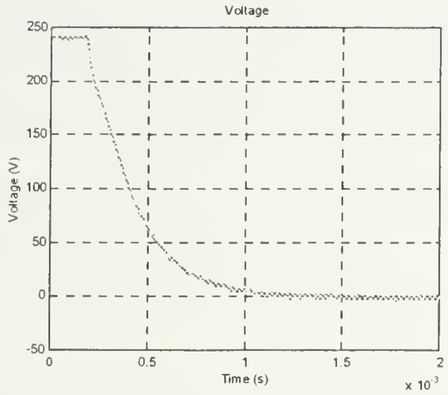

Figure 4.1 Voltage Across Rails

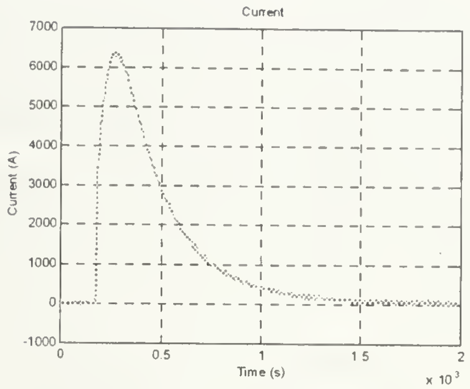

Figure 4.2 Current Through Rails

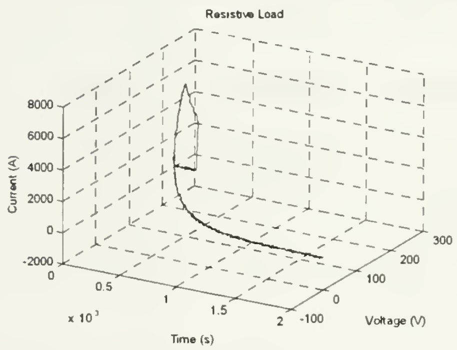

Figure 4.3 3-D Plot of Current, Voltage and Time.

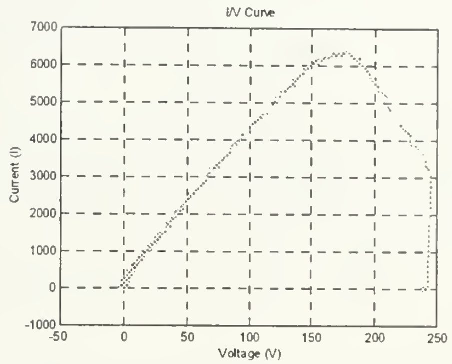

Figure 4.4 I/V Curve

Interestingly, the straight rising portion of the I/V curve in figure 4.4 has an inverse slope of 25 mΩ which is the measured resistance of load.

Because the force on the projectile goes as the current squared we examined different pulse shapes to determine their effect on the force. To create the different shaped pulses we fired a the capacitors into a pure resistive load (Curve 1), the resistive load and a 14 μH inductor (Curve 2), and the resistive load and two 14 μH inductors (Curve 3). The current wave forms were stored and a MATLAB program was written which integrated over the current curve and the current squared curve by using the trapezoidal method of numerical integration. The effect of adding the inductance to the circuit was lengthening the pulse and reducing the amplitude.

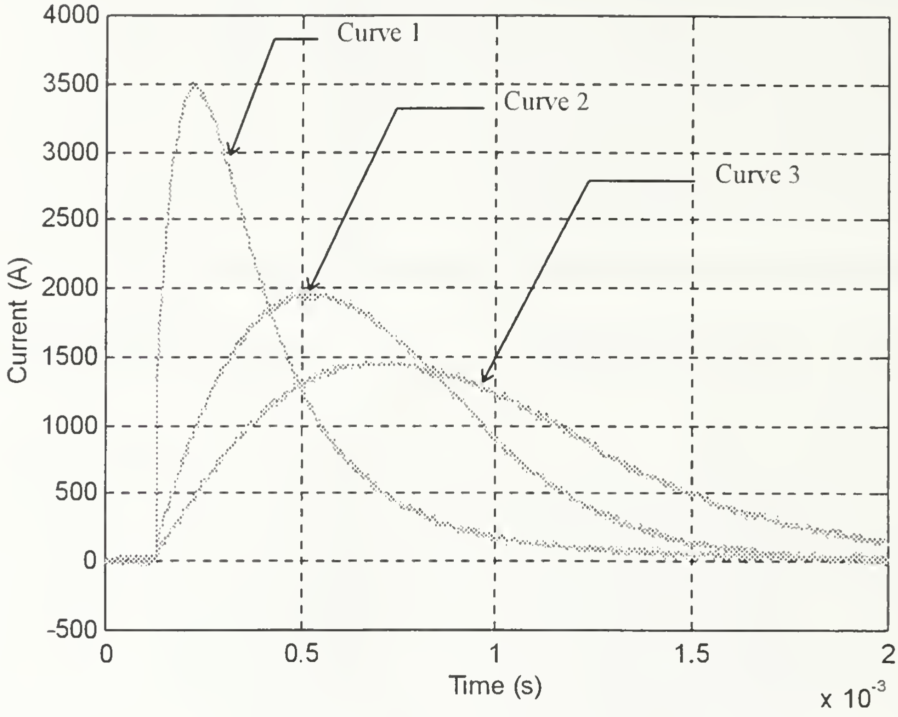

Figure 4.5 Current Pulse Shapes

The integration of the I^2 curve (Table 4.1) showed that the lower the inductance the greater the area under the curve and therefore the greater the resultant force. To insure that the larger value for I^2 curves was not a function of more charge being passed through the resistor inductor system the value of the total current was calculated and compared (Table 4.1).

Table 4.1 Area Under Current Curves in Figure 4.5

	Pure resister Curve 1	14 μH inductor with resister Curve 2	28 μH inductor with resister Curve 3
I (A)	1.2617	1.5249	1.5562
I^2 (A^2)	2700.3	2167.7	1672.9

From the data, curve 1 had the lowest total current but would have led to the highest force on the projectile. This leads one to conclude that the optimal current pulse is one which dumps all the current possible as quickly as possible. The disadvantages of this method are that all the acceleration occurs over a shorter portion of the rails possibly increasing the wear on the rails and that the quick rise time on curve 1 increases the "jerk" experienced by the projectile. In an operational rail gun system for a tank the force on the projectile as a function of pulse length and amplitude must be balanced against the length of gun needed to achieve the desired accuracy at extended ranges and rail wear.

D. EXPERIMENTAL VALIDATION OF THEORY

In Chapter II two different techniques were used to derive an expression for the force and subsequently the velocity of the projectile. Using the dimensions of the test gun we find that both derivations yield nearly identical values for the force. The estimated force on the projectile using the Lorentz Force derivation and equation 2.10 yields:

$$F = 2.8\mathrm{x}10^{-4}\, I^2 \tag{4.1}$$

Using equation 2.19 for force derived by treating the rail gun as a part of a circuit yields:

$$F = 3.0\mathrm{x}10^{-4}\, I^2 \tag{4.2}$$

The difference between these two derivations can be traced to the assumptions on where the current flows through the rails. The first derivation assumed the current traveled through the center of the rails and the second assumed that the current traveled uniformly throughout the cross section of the rails. The stored current pulses from each shot were used as described earlier to determine the value for I^2 and calculate the expected values for the velocity. Table 4.2 shows the results of five shots. All five shots fired similar projectiles positioned 2.5 cm forward of the circuit rail connection, with the capacitor bank charged to 250 volts, and with no air injection or permanent magnet augmentation.

Table 4.2 Comparison of Experimental Data with Theory without Magnets

Shot	Measured Velocity (m/s)	Equation 4.1 (m/s)	Equation 4.2 (m/s)
1	6.76	9.66	10.45
2	7.96	9.83	10.64
3	5.31	7.90	8.55
4	7.94	9.41	10.18
5	11.2	11.97	12.96
Average	7.82	9.75	10.55

From the data we see that both derivations predict higher values for the velocity than are experimentally observed and that equation 4.1 is closer to the measured values. The lower measured values can easily be explained by the fact that friction and air drag have been ignored.

Another energy loss mechanism which impacted efficiency which was not considered is heat. Each round after firing is hot to the touch. The armature heating occurs from resistive losses. This effect was difficult to quantify.

E. AUGMENTATION EFFECTS

1. Magnets

The permanent magnet augmentation of the railgun has its most significant impact at lower currents because the force due to the permanent magnetic field is proportional to the current where as the force from the induced magnetic field is proportional to the current squared. The force on the projectile estimated from equations 2.23 a and b is:

$$F = 2.8 \times 10^{-4} I^2 + 1.4 \times 10^{-3} I \tag{4.3}$$

or

$$F = 3.0 \times 10^{-4} I^2 + 1.4 \times 10^{-3} I. \tag{4.4}$$

This augmentation technique is the most help is when for some reason there is an increased circuit impedance caused by a break or degradation in contact between the rails and the armature. The force from the permanent magnetic field could be enough to keep the armature going until good contact is reestablished further down the rails and high current reestablished. To test the effects of the permanent magnets shots were fired with and without the magnets. Table 4.2 contains data for shots without magnets, Table 4.3 contains data for shots with magnets, and Table 4.4 compares the averages between the two. As without the magnets the estimated velocities exceed the measured velocities because friction and drag were ignored.

Table 4.3 Comparison of Experimental Data with Theory with Magnets

Shot	Measured Velocity (m/s)	Equation 4.3 (m/s)	Equation 4.4 (m/s)
1	14.25	23.38	24.52
2	15.82	22.21	23.30
3	11.80	18.88	19.75
4	15.72	19.67	20.59
5	17.36	23.31	24.45
Average	14.99	21.49	22.52

The shots with the magnets were on average 85% faster than the shots without the magnets. Only part of the increase in velocity can be attributed to the force acting on the projectile. The other contribution which can be attributed to the magnets is that more current was discharged through the projectiles traveling through the permanent magnetic field. On average there was 13.4% more current passing through the armatures with the permanent magnets than those without. (Table 4.4).

Table 4.4 Average Measured and Predicted Values for Velocity with and without Magnetic Augmentation.

	Measured Velocity (m/s)	Lorentz Velocity (m/s)	Circuit Velocity (m/s)	Charge Transferred (C)
Magnets	14.99	21.49	22.52	2.7191
No Magnets	7.82	9.75	10.55	2.3960

A possible explanation for why a greater amount of charge is transferred with magnets than without them could be that the magnets facilitate better connection between the armature and the rails. The force due to the magnets dominate at the low currents. Therefore as the capacitors discharge there is more movement during the current rise with the magnets than without. The movement reduces the arcing, which is one of the significant energy loss mechanisms. As a result, not only is the force acting on the projectile increased by a term proportional to the current but is also increased because there is less arcing as the projectile moves and more current flows.

2. Air Injection

Air injection had no significant effect on the muzzle velocity of the projectiles. The purpose of the air injection was to provide an initial velocity and overcome static friction. The air injection could not overcome the static friction between the rails and the armature when the armature had good contact with the rails. When the rails and armature were modified to allow the air injection to overcome the static friction, the connection between the rails and the armature was too poor to allow sufficient current to flow through the circuit.

To quantify the effects of the air injection several shots were taken with the air pulse only, with the air pulse and capacitor discharge and with the capacitor discharge only. The resistance between the two rails through the armature was used as a

measurement of the connection between the rails and the armature. The higher the resistance the poorer the connection. For the shots throughout this work when not testing the air injection the measured resistance was below 30 mΩ. The projectile achieve a velocity of 8 m/s when fired with only and air pulse and the rails separated enough so that there was no contact between the rails and armature. As the contact between the rails and the armature increased, the muzzle velocity decreased. At resistances around one ohm, the armature failed to exit the barrel. At resistances less than 0.5 Ω the projectile failed to move a measurable distance along the barrel. When firing with the air injection, capacitor discharge, and resistance between the rails and armature less than 30 mΩ, the measured muzzle velocity was around 7.8 m/s which is the same as firing without the air injection. When firing with the air injection, capacitor discharge and resistances greater than 0.5 Ω, the projectile velocities were less 5 m/s and in most cases were unmeasurable because they did not travel the 1/4 m required to break both laser beams.

F. CONCLUSIONS

Electromagnetic launch technologies hold considerable promise for future military applications in the areas of anti-tank weapon, and missile defense systems. EM launch technologies may be the best technologies available to defeat the reactive armor designs which are starting to appear. They also provide significant advantages in tank survivability and reduced logistics because of the elimination of the explosive propellants from anti-tank rounds. Considerable advances are still needed in the areas of rail and armature design, pulse power supply, and field hardening of the rails and power supply. A national effort must remain focused in these areas.

A small scale rail gun like the one described in this work can be a valuable tool in understanding the performance of armature and rail designs, and effects of augmentation techniques.

Permanent magnet augmentation increased the velocity of the projectile by 85%. The augmentation of the system with the air injection proved to have no effect at the pressures available to this work.

The hybrid armature design proved to be the most effective in terms of velocity and rail wear .

check up

f research this gun could be useful in are armature design, rail
gmentation techniques. One could easily experiment or run
/ different types of conducting materials for rail construction
r, rail wear, and armature velocity. Along with the variations
rials and designs for armatures could be tried in concert with
the different rails until an optimal match is found. Once the optimal rail and armature design is established they can be applied to higher energy railguns.

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